CHAPTER III

JOINT TYPHOON WARNING CENTER STUDIES

A. An Analysis of Tropical Cyclone Wind Velocity Forecasting Accuracy.

1. BACKGROUND:

A revised technique for forecasting maximum wind velocities was used in 1969. It is based on a smooth curve extrapolation of central pressures along the forecast track. The forecast central pressure and forecast latitude are used as arguments to enter the JTWC pressure/wind correlation to obtain a forecast velocity. Modification of this initial forecast velocity is made subjectively according to the storms position with relation to the subtropical ridge, divergence patterns along the track, cloud organization as depicted by satellites and the sea surface temperature gradients when appropriate.

2. DISCUSSION:

Errors in forecasting by this technique result from:

a. Normal instrument and/or reporting error in central pressures reported by reconnaissance aircraft.

b. Latitude error in the forecast track.

c. Failure of the intensity curve to follow the pattern established during early phases of the storm.

Aircraft dropsonde pressures are used on the confidence level of ± 5 mb. Both instrument error and minor differences in the placement of the dropsonde relative to the absolute minimum pressure in the eye on consecutive soundings are included in this confidence level. An analysis of the past several soundings is used to determine a consistent trace. Low level aircraft penetrations with direct readings of pressure improve the confidence level somewhat and provide anchor points for the tendency curve.

Errors in forecast latitude displace the entry on the pressure-wind correlation graph but generally contribute only 5 knots or less to the total error.

The primary source of error resulted from the breakdown of the extrapolation assumption when, as with typhoon Ida, a 55 millibar deepening was observed over an 18 hour period. Some typhoons go through more than one phase of intensification or do not follow a simple intensification-decay cycle.

3. DATA:

Table 3-1 records the 1969 season verification of maximum wind forecasts at warning time and all forecast times.

Figure 3-1 is the 24 hour maximum wind forecast verification for individual typhoons of 1969.

Figure 3-2 is the frequency distribution of errors for 12, 24, and 48 hour forecasts of maximum winds.

Table 3-2 records the 1966 season verification for purposes of comparison.

4. ANALYSIS:

During the first 48 hours of each forecast period in 1969 absolute mean error increased at a mean rate of 2 knots every 6 hours from an initial error of 4.9 knots at warning time. The algebraic mean error was minus in all time categories indicating a forecast bias on the low side. The low bias increased from 1.9 knots at warning time to 6.8 knots at 48 hours.

The largest intensity errors were associated with the two most intense typhoons (Viola and Elsie), together with Typhoon Ida whose rate of intensification was unusually rapid and with Typhoon Susan, an off-season typhoon that ignored climatology in reaching 105-knot sustained velocity. Only these four typhoons significantly exceeded the mean absolute 24 hour forecast error of 13.7 knots.

The 24 hour intensity error distribution ranged from -45 to +35 knots with the median forecast 5 knots low and three-fourths of the forecast errors falling between -25 and +15. The 48 hour intensity error distribution ranged from -55 to +60 with the median forecast 5 knots low and three-fourths of the forecast errors falling between -35 and +10.

It is evident from the appearance of the forecast error distribution curves (Figure 3-2) that maximum wind forecast error increases with time and shows little skill at 48 hours. The median 12 hour forecast is accurate within ± 10 knots; the median 24 hour forecast is accurate within ± 37.5 knots.

In order to evaluate the relative success of the central pressure forecasting technique, the same analysis was made of the 1966 season accuracy of forecasting maximum winds. The results are reported in Table 3-2. Comparison shows a significant improvement in 1969. This is attributed to increased emphasis on forecasting maximum wind velocity and the effectiveness of the central pressure technique devised for this purpose.

5. CONCLUSIONS:

Forecasts of maximum wind for 12 and 24 hour time periods in 1969 have mean absolute accuracies of 9.0 and 13.7 knots respectively with a 5 knot bias toward underforecasting. These figures reflect a significant improvement over the 1966 season and indicate that the procedure described in this section is effective.

6. ACTION:

Continued use of the central pressure method of forecasting maximum winds is indicated for 1970 with an attempt to correct the tendency for slight underforecasting.

a. The algebraic mean values might suggest that forecasts could be improved in 1970 by merely increasing all forecasts by 5 knots, however, the frequency distribution in Figure 3-2 shows a modal value at zero error. Simply displacing the complex curve five knots to the right would not improve the distribution significantly. If the curve were pictured as symmetric with the errors on the positive side, the excess of forecasts in the range 10 to 25 knots too low becomes evident.

b. A study of these cases is indicated as the best way to improve performance in 1970. A further improvement may be realized from a climatological approach to mean rates of intensification. The climatic average values for the season used as minimum intensification forecasts should reduce the number of underforecast cases and produce a slight positive bias in mean values with a better centralized distribution.

TYPHOON INTENSITY VERIFICATION

	ABSOLUTE MEAN ERROR (KTS)					ALGEBRAIC MEAN ERROR (KTS)				
		FORECAST					FORECAST			
STORM	WARNING (CASES)	12-HR (CASES)	24-HR (CASES)	48-HR (CASES)	72-HR (CASES)	WARNING (CASES)	12-HR (CASES)	24-HR (CASES)	48-HR (CASES)	72-HR (CASES)
PHYLLIS	10.0 (21)	11.1 (19)	10.6 (16)	16.2 (12)	24.0 (4)	-1.0 (21)	+ 4.7 (19)	+ 7.1 (16)	+16.2 (12)	+24.0 (4)
SUSAN	8.9 (21)	15.9 (19)	20.8 (21)	39.5 (13)	33.3 (4)	-8.9 (21)	-14.1 (19)	-19.7 (21)	-34.5 (13)	-26.7 (4)
TESS	4.0 (10)	9.3 (7)	13.8 (8)	25.0 (1)	- (0)	+1.0 (10)	+ 6.4 (7)	+ 2.5 (8)	+25.0 (1)	- (6)
VIOLA	2.9 (24)	9.1 (23)	17.7 (22)	27.5 (16)	35.8 (6)	-0.8 (24)	+ 3.5 (23)	- 3.2 (22)	-21.9 (16)	-35.8 (6)
BETTY	2.0 (15)	7.1 (12)	12.7 (11)	9.2 (6)	15.0 (1)	-0.7 (15)	+ 0.4 (12)	0.0 (11)	+ 9.2 (6)	+15.0 (1)
CORA	1.0 (25)	3.2 (28)	7.4 (29)	13.2 (22)	15.6 (8)	+0.2 (25)	+ 2.1 (28)	+ 2.9 (29)	+ 1.8 (22)	- 5.6 (8)
DORIS	1.7 (9)	4.3 (7)	10.0 (5)	15.0 (1)	- (0)	-0.6 (9)	- 4.3 (7)	- 4.0 (5)	+15.0 (1)	- (0)
ELSIE	5.3 (31)	10.2 (28)	17.2 (30)	34.5 (22)	46.7 (9)	-0.8 (31)	- 0.5 (28)	- 2.8 (30)	0.0 (22)	- 3.3 (9)
GRACE	6.0 (29)	6.5 (23)	14.2 (25)	26.5 (17)	38.0 (5)	-4.3 (29)	- 2.6 (23)	- 9.4 (25)	-10.0 (17)	- 4.0 (5)
HELEN	6.7 (15)	11.4 (14)	13.6 (14)	31.9 (8)	12.5 (2)	-6.0 (15)	-11.4 (14)	-12.9 (14)	+ 0.6 (8)	-12.5 (2)
IDA	4.8 (24)	12.7 (22)	18.9 (22)	31.6 (16)	55.8 (6)	-4.0 (24)	- 7.3 (22)	-13.4 (22)	-30.3 (16)	-55.8 (6)
JUNE	5.6 (27)	8.5 (24)	9.3 (27)	10.3 (18)	17.1 (6)	0.0 (27)	- 3.1 (24)	- 5.6 (27)	- 9.2 (18)	-15.7 (7)
KATHY	3.2 (22)	8.3 (20)	10.0 (18)	12.1 (14)	11.0 (5)	+1.4 (22)	+ 5.3 (20)	+ 7.2 (18)	+ 3.6 (14)	- 7.0 (5)
ANNUAL TOTAL	4.9 (273)	9.0 (246)	13.7 (248)	22.9 (166)	30.2 (57)	-1.9 (273)	- 1.4 (246)	- 4.2 (248)	- 6.8 (166)	-13.3 (57)

TABLE 3-1

TYPHOON INTENSITY VERIFICATION

1966

	ABSOLUTE MEAN ERROR	ALGEBRAIC MEAN ERROR
	24-HR	24-HR
ANNUAL TOTAL	17.2 KTS	—3.4 KTS

TABLE 3-2

1969 TYPHOON INTENSITY ERRORS FOR 24 HOUR FORECASTS

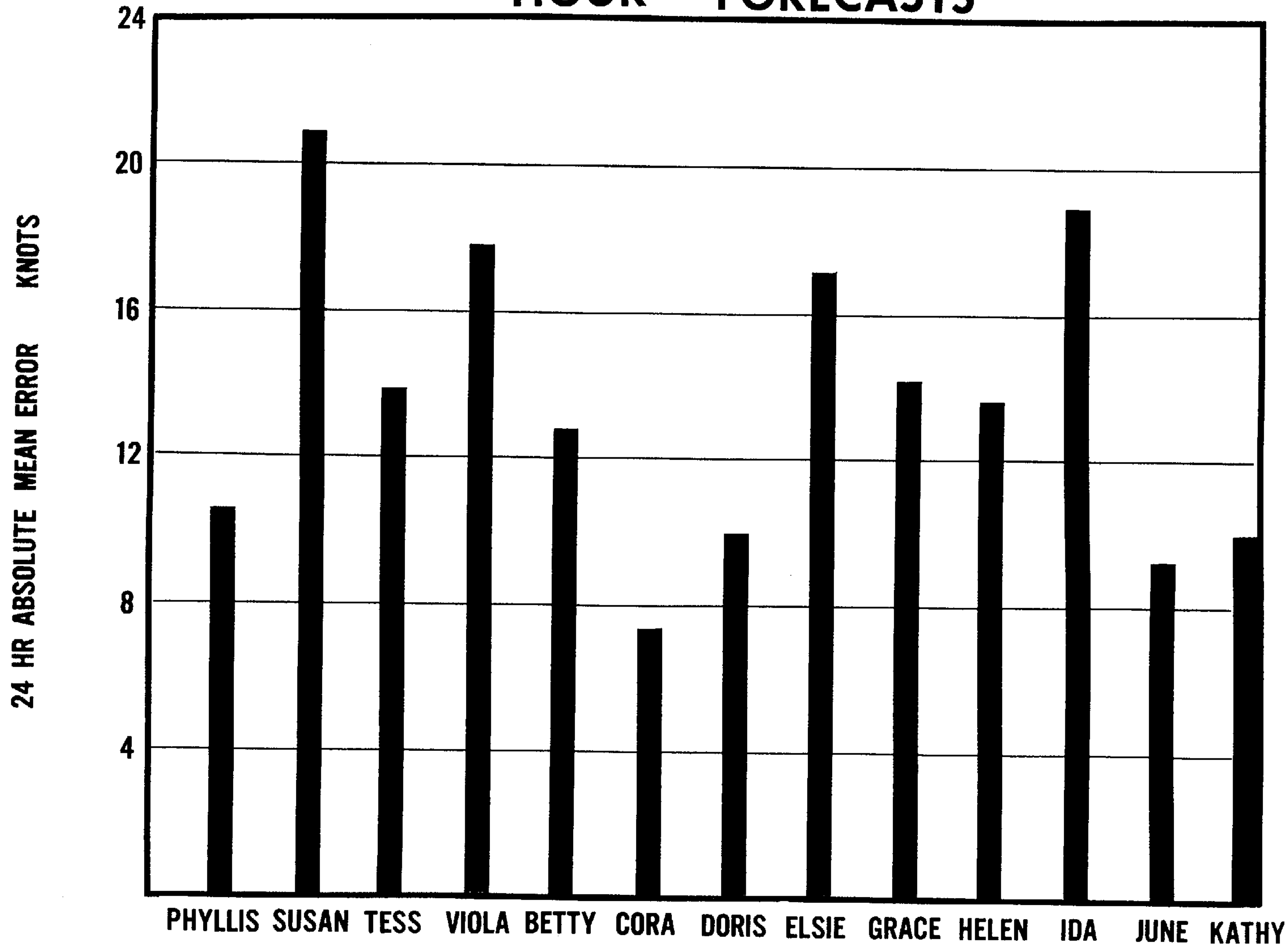


FIGURE 3-1

INTENSITY FORECASTING SKILL 1969

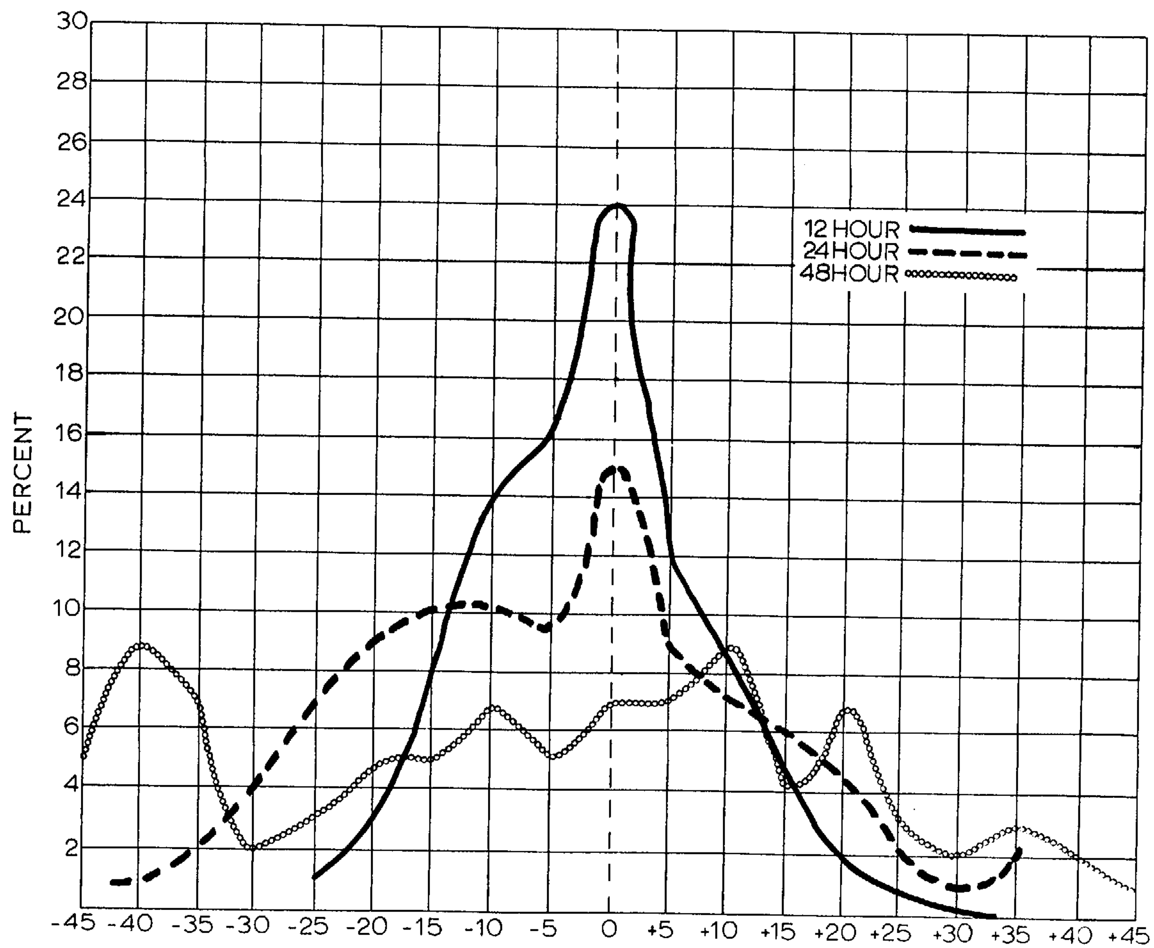


FIGURE 3-2

B. A Discussion of Tropical Cyclone Forecast Verification Methods and Seasonal Differences in Forecasting Difficulty.

1. GENERAL:

a. Mean Error: The verification method for tropical cyclone forecasts used since the establishment of JTWC has been mean absolute error, with the 24 hour error receiving the most attention. (See Figure 4-1)

b. Right Angle Error: Recognition of some basic inadequacies of the mean absolute error led to addition of the right angle error charts (See Figure 4-3) to depict track forecasting ability apart from speed errors.

c. Median Error: Occasional large forecast errors contribute disproportionately to the annual mean error as seen in Figure 3-3. All mean values are greater than their corresponding median values. In 1969 the median error for the over 200 MI cases was 265 MI. Six errors of 70 MI are needed to balance 200 MI errors. The extreme effect of this could be seen in 1960 when multiple storms, overtaxed reconnaissance resources and erratic tracks combined to produce more large forecast errors and resulted in a spread of 46 N.M. between median and mean values. Median error provides a more conservative and meaningful measure of forecast accuracy for the season. Since median error represents the 50 percent confidence level, any desired specific and significant point in the frequency distribution of errors (67%, 75%, 80% or 90%) could be selected as a more valid measure of skill than the mean absolute error. The few large forecast errors that do occur would contribute equally to the combined figure on a one forecast-one vote basis. It is interesting to note that both 1968 and 1969 median scores of 97 N.M. were records for the 11 year period of record.

d. Seasonal Differences: The increased difference in 1969 between the median score of 97 N.M. and the mean score of 111 N.M. illustrates the influence of a few large errors on the annual mean in a "light" typhoon year. The 1968 and 1969 seasons both had six recurving typhoons and a similar number of opportunities for large error during recurvature or on northeasterly accelerating storms even though the total number of warnings issued in 1969 was only about half of the 1968 total. Through midseason 1969 including Typhoon Doris the JTWC absolute mean error was 89 N.M. The influence of recurving Typhoons Grace, Helen, Ida, June, and Kathy was not balanced by any straight-running, late-season cyclones. The year ended with a respectable but disappointing 111 N.M. mean error. The potential for breaking 100 N.M. in mean error for a season remains good but depends on limiting the larger errors and the chance occurrence of well-behaved cyclones. This illustrates a basic difficulty in evaluating forecaster performance from year to year in the tropics. A sample of 100 tropical cyclones might constitute a representative sample of all situations

24 HOUR MEAN AND MEDIAN ERRORS FOR JTWC TYPHOON FORECASTS

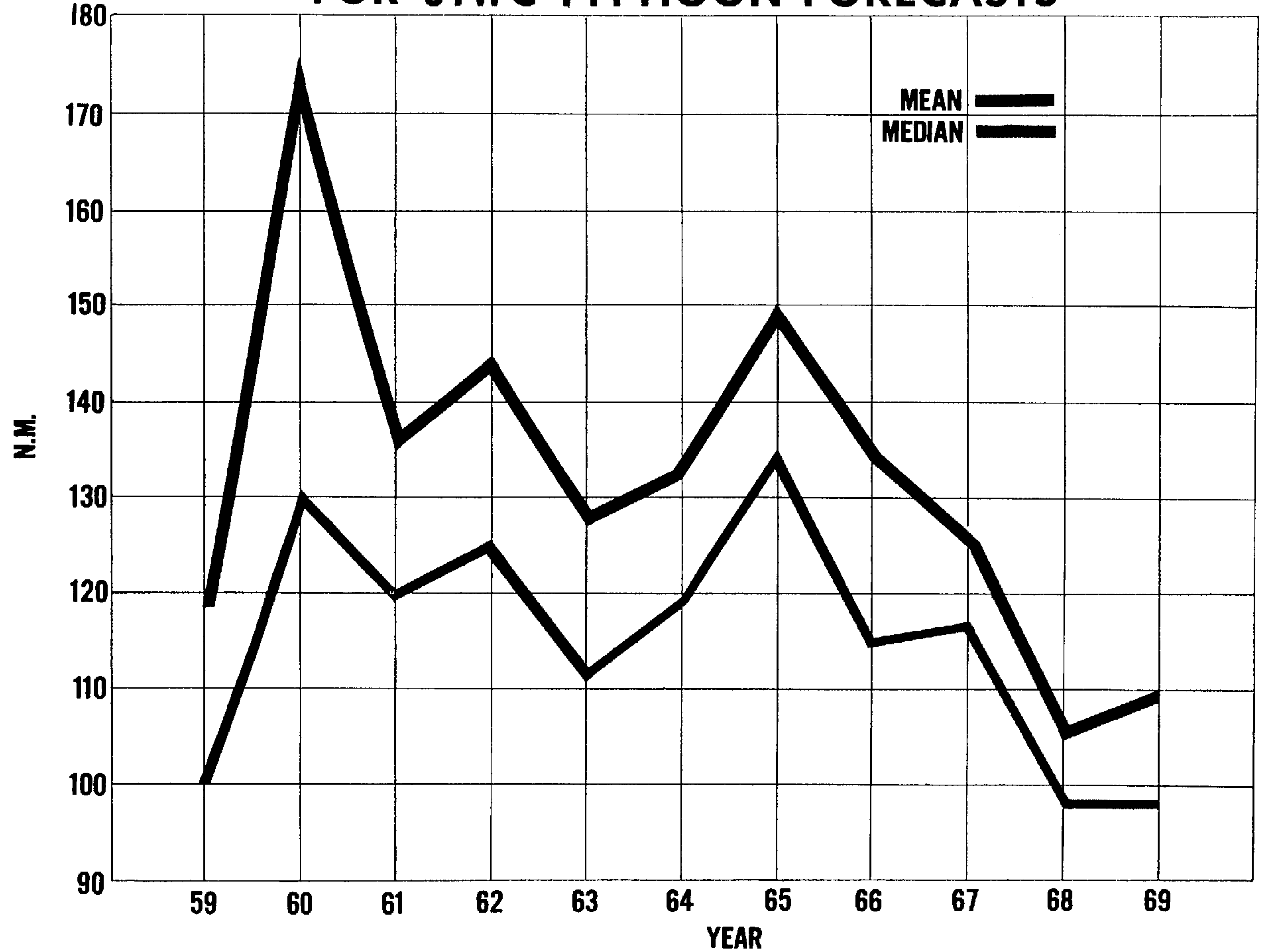


FIGURE 3-3

faced by the forecaster at one time or another, but a one-season sample of 20 or 30 cyclones is liable to contain a disproportionate number of recurving or erratic cyclones, resulting in a relatively high mean error. A sample containing straight-running cyclones, on the other hand, would produce a cushion of better than average forecasts. A method of evaluation including a measure of forecast difficulty would provide a more realistic appraisal of forecaster performance.

e. Displacement as Measure of Difficulty: A skill-scoring method sometimes mentioned for extratropical storms is based on error as a ratio of actual displacement during the forecast period. This method was used by LCDR Jerry Jarrell of Naval Weather Research Facility to examine JTWC annual forecast verifications from 1959 through 1967. (unpublished) The study has been updated for 1968 and 1969 and is presented graphically in Figure 3-4. The assumption made in this approach was that if a cyclone moves 500 N.M. in a 24 hour period, an error of 100 N.M. shows more skill than if the cyclone moved only 250 N.M. in the same period. In this system forecast errors are expressed as miles of error per mile of movement rather than the usual miles of error per 24 hour time period. In the first case the error rate would be 100/500 or .200. The error rate of the second example would be 100/250 or .400.

An implication of this system applied to individual forecasts is that slow-moving storms are easier to forecast than fast-moving storms. Such is not alwyas the case, as illustrated by recurving storms which execute the greatest change of direction and present the most difficult forecasting situation while moving at their slowest speed. The error-producing combination of deceleration, rapid change of direction and then acceleration challenge the ability of any forecaster. Even though the 24-hour distance moved in a recurve track is the same as that on a straight track, the recurving storm is a much more difficult one to forecast. A quasistationary storm could never score well in the system because of the small denominator in the skill ratio. An excellent verification error of 50 N.M. made while the storm only moved 75 miles would not appear to have much skill. Applied to yearly mean values the system may avoid objections raised on the basis of individual forecasts. In the application of this technique to JTWC forecasts the mean displacement value and mean error are used to produce mean error ratings for each year. The variability of individual years in mean displacement values is evidence of significant differences in mean storm behavior from year to year. Under this rating system the 1969 season with a mean 24-hour speed of 12.4 knots for all typhoons would be more difficult to forecast than the 1968 season when a mean 24-hour speed of 9.2 knots was recorded. Compared with the past 11 years the 1969 season ranked 1st in difficulty and 1st in accuracy by the mean error to displacement ratio.

f. Objective Technique Scores as a Measure of Difficulty: A second indication of basic differences between

MEAN ERROR TO DISPLACEMENT RATIO

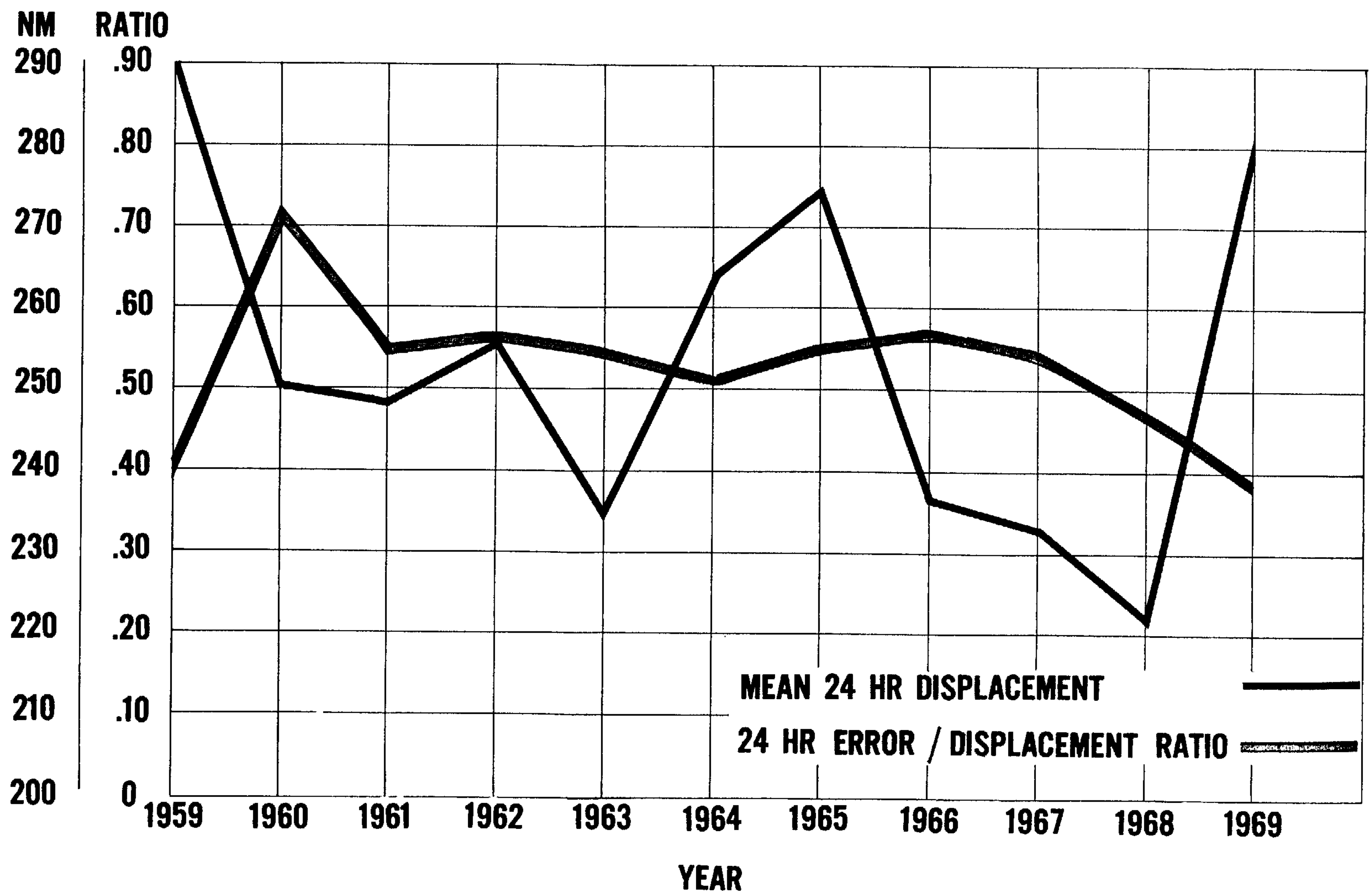


FIGURE 3-4

seasons is the variability noted in extrapolation and Arakawa objective technique scores in Table 3-3. The samples used in constructing the table included forecasts for tropical cyclones of all classes. (The JTWC values in this sample therefore may differ from official verification figures which include only those cyclones reaching typhoon strength.)

EXTRAPOLATIVE TECHNIQUE SCORES

YEAR	JTWC	EXTRAP	ARAKAWA
1967	121 NM	136 NM	NOT USED
1968	103 NM	108 NM	119 NM
1969	121 NM	131 NM	137 NM

TABLE 3-3

Extrapolation as used at JTWC includes a considerable amount of subjective judgement by the forecaster. The extrapolation forecast is usually the starting point for each official forecast. The fact that official forecasts have improved upon intelligent extrapolation by 5% in 1968, 9% in 1969 and 11% on a small sample in 1967 indicates a consistent mean skill on the part of the JTWC forecasters to do what they purport to do-forecast typhoon movements. A function of the difference between extrapolation error and mean error might serve as a measure of forecaster skill and JTWC performance. The Arakawa technique has consistently proved to be the best of truly objective techniques. This method eliminates the subjectiveness of extrapolation and may reflect the differences in difficulty between seasons better than any other simple method. The technique is firmly based in extrapolation. Errors recorded by this technique should be a good measure of the amount of nonsteady state change occuring. The 1969 mean Arakawa error of 137 N.M. compared to the corresponding 1968 value of 119 N.M. is interpreted to indicate that 1969 cyclones were more irregular in movement than those of the previous year, a fact well supported by personal observation.

2. CONCLUSIONS:

a. An objective means of rating the difficulty of a typhoon season should be considered in addition to the single value of mean or median accuracy. The Arakawa technique is favored for this purpose.

b. Median scores should be included in future annual reports as an alternate measure of forecast accuracy.

c. The error to displacement ratio is not considered an indicator of forecasting skill, but displacement serves to point out the differences in storm behavior between one season and another.

C. Frequency Distribution of Error in JTWC Official Forecasts.

1. BACKGROUND:

Operational use of JTWC tropical cyclone warnings requires an appreciation of the frequency and nature of forecasting error likely to be encountered. This article is an effort to describe the frequency distribution to form a realistic basis of understanding for both the operational user and the JTWC forecaster.

2. PROJECT SCOPE AND DESIGN:

Mean 24-hour absolute errors on all storms designated as typhoons from 1959 to the present were counted and totaled by 10-knot intervals. The total frequencies were graphed and a smooth-curve analysis made (See Figure 3-5). A total of 4236 forecasts were included in the study. In order to provide an operationally useful tool the individual interval totals were converted to cumulative percentages for two periods: 1959-1967 and 1968-1969. (See Figure 3-6.) It is difficult to estimate whether the improved performance of the last two or three seasons can be maintained in future typhoon seasons. Both curves have been presented to show the long-time and recent experience.

3. DISCUSSION:

The cumulative percentages on the Y-axis can be used as desired levels of confidence to find the error margin in N.M. associated with this confidence level on the X-axis.

CONFIDENCE TABLE

LEVEL	59-67 (NM)	68-69 (NM)	IMPROVEMENT
50%	118	97	17.8%
67%	162	126	22.2%
75%	186	147	21.0%
80%	206	164	20.4%
90%	260	220	15.4%

TABLE 3-4

FORECAST ERROR FREQUENCY DISTRIBUTION 1959-1969

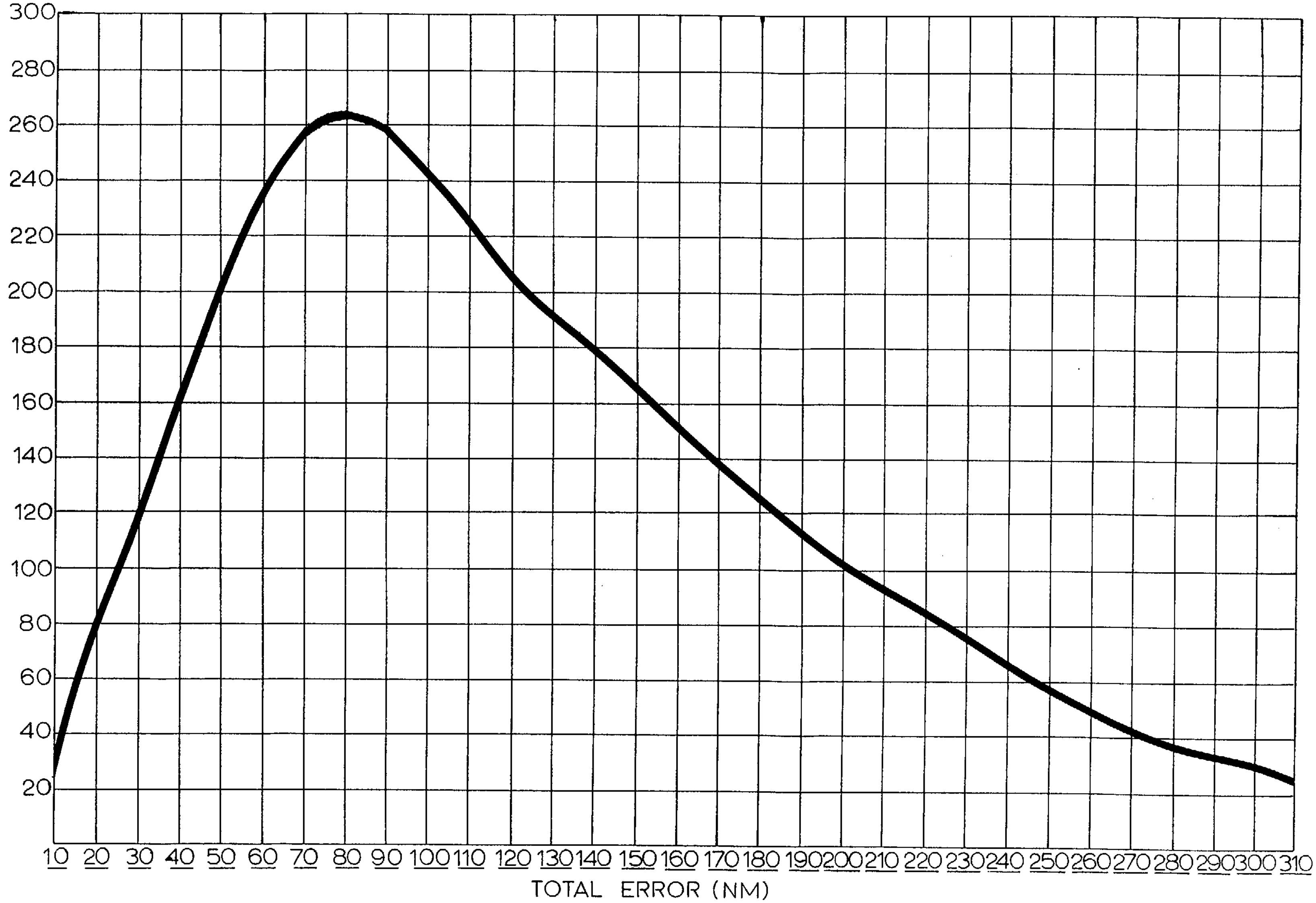


FIGURE 3-5

CUMULATIVE PERCENT OF FORECAST ERROR BY MILES OF ERROR

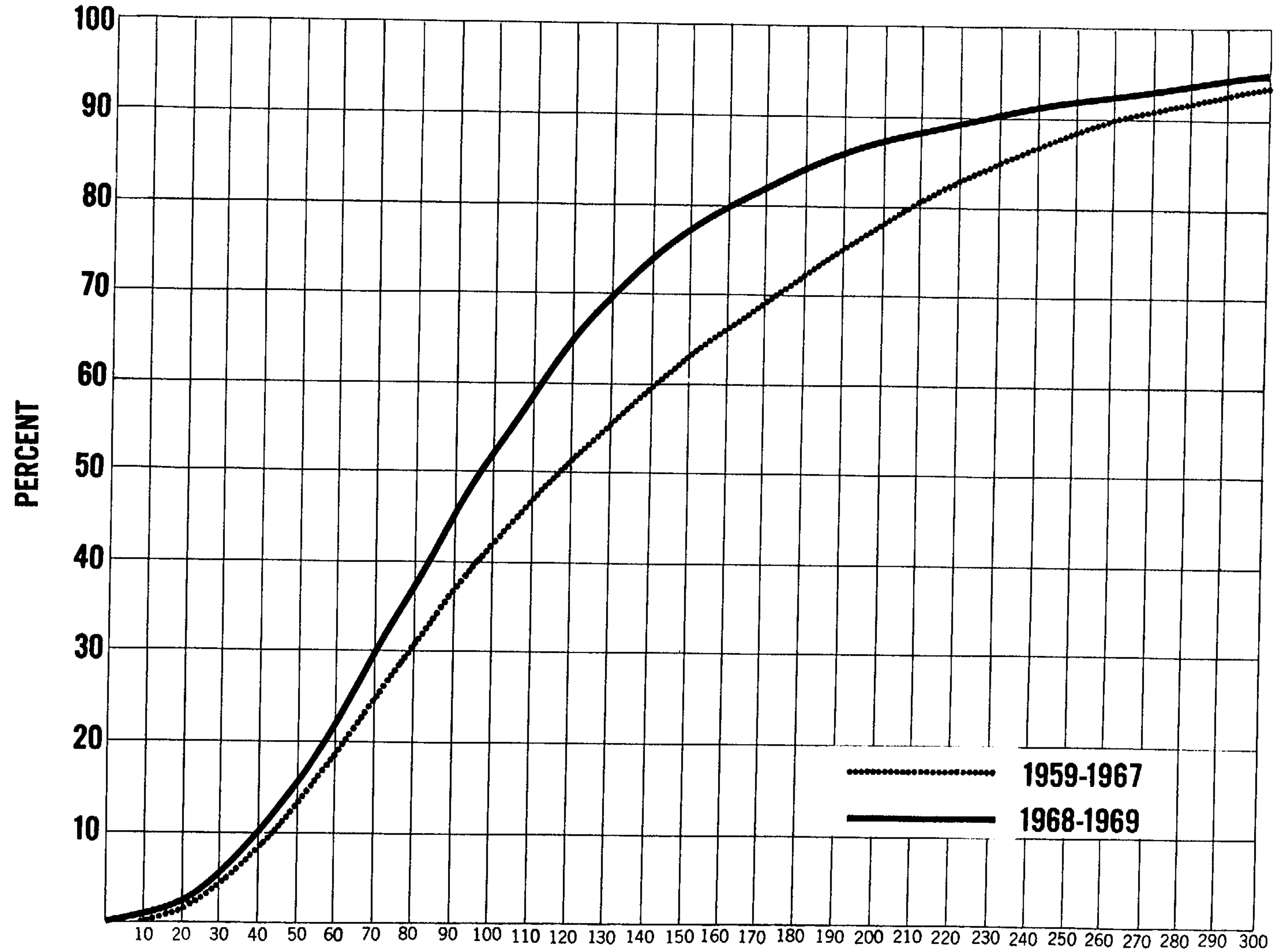


FIGURE 3-6

4. CONCLUSIONS:

a. It is noted that even though median and modal scores have reached record accuracies in 1968 and 1969, they don't measure the full extent of the forecast improvement realized. The maximum improvement is recorded near the one sigma level with over 22% improvement made in two-thirds of all forecasts.

b. The area of major improvement in the curve was between 40 N.M. and 160 N.M. and in this area represents a 30 to 40 N.M. increase in confidence level.

c. The failure to limit large errors is evident as the 90% and greater confidence levels are entered. Less improvement has been made in the upper 10 percent than in the average forecast range.

d. The incidence of errors exceeding 200 N.M. has been reduced from 21% to 12% but remains the necessary area of concern both because of the disproportionate influence on mean values and the potential for severe weather damage due to lack of adequate or timely warnings.

e. Very little improvement has been realized in the upper 5%. About 15 or 20 forecasts per year are so unpredictable that 24-hour errors will exceed 300 N.M.

f. In addition to this graphic approach to confidence level, the nature of each forecast situation should be considered. A storm moving in a northeasterly direction is, for instance, less accurately forecasted than other situations.

D. Causes and Cures for Forecast Errors Exceeding 200 N.M.

1. GENERAL:

A study of errors over 200 N.M. for the 1968 season was made to determine contributory factors and identify areas of possible improvement.

It was noted that the individual characteristics of each storm predispose large forecasting errors. Eleven of the 20 typhoons of 1968 had no forecasting errors greater than 200 N.M. The nature of each storm is, however, more a matter of hindsight rather than an evident feature of a storm prior to onset of looping, acceleration or generally erratic movement. Errors over 200 N.M. occur during all phases of the life cycle of tropical cyclones. In 1968 the early phases of a storm accounted for one-fourth, the late phases for one-fourth and the mature stage for the remaining one-half of large errors. The six identified factors contributing to large errors were:

a.	Forecaster Technique	1/6
b.	Misleading Recon Data	1/6
c.	Lack of Recon Data	1/6
d.	Looping Motion or Quasistationary Periods	1/6
e.	Acceleration on Northeasterly Track	1/6
f.	Unusual Motions to Southwest or Sharp Recurvature etc.	1/6

Fujiwhara motions would also result in large errors but have not been common in 1968 or 1969.

Improvement of individual forecasts in the six categories is the present subject of JTWC operational research. The study of forecaster confidence reported in this annual points up the basic inability of the forecaster to anticipate large errors in many situations. Even under those circumstances when he can recognize the potential for large error, he is able to limit his error to average values in only half of the cases.

A forecaster's handbook for JTWC is being prepared as an aid to improve forecaster technique in minimizing these errors, particularly those resulting from misleading reconnaissance data.

The lack of reconnaissance data during the first 12 to 18 hours of warning of many developing storms is common. When a daylight investigation locates a depression, continuous reconnaissance is generally planned for the following morning. If the cyclone is moderately well developed when first located or forecasted to develop rapidly, fixes are requested as soon as possible. During the initial period of development prediction of the direction of movement of tropical cyclones is frequently not very successful. Only after two or three "fixes" are we able to state with good confidence where the cyclone is or is going. The selection of the initial track is made on the basis of climatology, synoptic steering, and various objective techniques. Because of aircraft scheduling problems and the need to place cyclones in warning as soon as their development can be predicted, only small improvement can be expected in this area in the future.

Looping motions are a two-edged sword to forecasting accuracy. The sometimes sudden deceleration finds two or three forecasts far overshooting the storm and a consequent acceleration out of the loop leaves two or three quasistationary forecasts far behind. A study of loop duration, exit speeds and directions and a means of anticipating the breakout will be undertaken to provide a degree of error reduction in this difficult situation.

A study of accelerations on northeasterly tracks reveals a persistent underforecasting of northeast movements during 1968 and 1969 as well as in many years past. The average 24 hour error for northeasterly moving storms in 1968 was 156 N.M. on 52 cases. The 1969 average of 127 N.M. for 45 cases was some improvement, but forecasts remained persistently behind actual acceleration. During 1969 ten of forty-five northeasterly forecasts were in advance of actual movement, none by more than 65 miles. In 1968 ten of fifty-two forecasts were in advance of actual movement, six of them on the same storm and three of these 160 to 180 N.M. in advance of actual movement.

The experience of 1968 and 1969 is being used to identify storms with an expected accelerating track to the northeast and to compensate for the persistent underforecasting of movement seen in past years in 1970 operational forecasting.

The final category of movements to the southwest, sharp recurvatures and other unusual actions will continue to produce a few large errors. The best hope for improvement in these storms that fail to follow extrapolation may be found in the analog technique now under development.

A follow-up study in 1969 found that three typhoons accounted for 72% of the 24-hour errors over 200 N.M. and all of the 24-hour errors exceeding 300 N.M. Elsie, Grace and June were the misbehaving ladies. Elsie settled down after a rather unpromising beginning but Grace and June remained erratic throughout their lifetimes.

E. A Comparison of Objective Techniques for Typhoon Movement.

1. STATUS:

Forecasts using seven different objective techniques were used and verified for all four warning times for all 24 hour forecasts issued by JTWC in 1969. Techniques showing the best results in 1968 were retained and those failing to show promise were discontinued.

2. 24 HR OBJECTIVE TECHNIQUES:

a. JTWC - official forecast for comparison.

b. EXTRAPOLATION - a semi-objective method by which forecast points are determined by recent past values of position, speed and direction.

c. ARAKAWA - grid overlay values of surface pressure are entered into regression equations and hand computed.

d. 700 mb PROG - HATRACK forecast based on 700 mb SR forecast fields.

e. 700 mb PROG MOD (12 Hr) - (d.) is modified by twice the recent 12 hr vector error.

f. 500 mb PROG - HATRACK forecast based on 500 mb SR forecast fields.

g. 700/500 mb PROG RENARD - method using HATRACK 700 mb longitude and HATRACK 500 mb latitude (reported in 1968 annual).

3. MODIFICATION TECHNIQUES:

a. A single correction vector equal to twice the most recent 12 hour error correction vector is applied to the 700 mb prog forecast to produce the 700 mb prog mod forecast.

b. A 12 hour history position is provided as an input to the TYRACK program. The apparent speed and direction over the past 12 hours is computed and used to select the best steering level and to correct the forecast steering of that level for observed differences from history.

4. TESTING AND RESULTS FOR 24 HOUR FORECASTS:

A homogeneous sample of 210, 24 hour forecasts, for tropical storms and typhoons was assembled for 1969. Results are summarized in Table 3-5. The following general observations are offered:

OBJECTIVE METHODS STATISTICS 1969
(24 HR MEAN VECTOR ERRORS N.M.)

STORM	(CASES)	JTWC	EXTRAP	ARAKAWA	700P	700P*	500P	RENARD	TYRACK
T. PHYLLIS	(13)	150	160	154	183	230	379	160	175
T.S. RITA	(3)	60	56	54	540	162	320	542	292
T. SUSAN	(5)	74	99	63	333	282	398	291	252
T. TESS	(3)	134	96	66	314	150	232	338	90
T. VIOLA	(14)	93	127	129	232	161	194	207	177
T.S. WINNIE	(3)	120	100	108	266	-	242	296	182
T.S. ALICE	(2)	195	222	243	123	-	171	171	276
T. BETTY	(9)	108	115	118	246	267	255	276	250
T. CORA	(25)	88	85	87	187	121	198	198	113
T. ELSIE	(23)	78	97	94	225	57	238	228	267
T. GRACE	(25)	186	254	337	292	222	398	278	505
T. HELEN	(14)	184	242	215	406	158	342	361	337
T. IDA	(20)	88	94	86	138	116	122	129	271
T. JUNE	(25)	140	138	123	170	100	244	141	205
T. KATHY	(17)	146	139	144	240	168	354	192	240
T.S. LORNA	(9)	129	156	108	268	201	314	218	150
ANNUAL MEAN VALUES	(210)	124	142	144	235	154	272	221	251

TABLE 3-5

* 700PROG MOD (12) has only 124 cases. Comparisons cannot be made on a homogeneous basis between this and other objective methods. Many of the missing forecasts involved extreme forecasts and were omitted as not meaningful.

a. JTWC official forecasts are again significantly better than any single objective technique.

b. Extrapolation continues to be the single most reliable objective technique. The 1969 extrapolation error of 142 N.M. increased 28 percent over the 1968 value of 111 N.M. The improvement over extrapolation of the JTWC official forecast increased from 5 percent in 1968 to 13 percent in 1969.

c. Arakawa forecasts remain very close to extrapolation and increased 16 percent over the 1968 value of 121 N.M.

d. The HATRACK 700 mb prog again verified better than the 500 mb prog but total error of 235 N.M. is excessive.

e. The 700 mb prog mod (12 Hr) - again improved on the performance of the unmodified forecast with performance approaching that achieved by the Arakawa surface pressure method.

f. The 700/500 mb prog Renard method again improved upon the performance of both the 700 mb and 500 mb HATRACK forecasts by 7 percent over 700 mb and 19 percent over 500 mb.

g. The TYRACK forecasts were disappointing in total accuracy but provided the most realistic and usable track forecasts during the season, particularly for recurving storms. Large speed errors continue and show need for additional program controls. The continued improvement in 48 and 72 hour right angle error is in part due to guidance from the TYRACK track forecast.

h. Individual forecasts in a non-homogeneous sample were examined from the viewpoint of determining the forecast method producing the individual absolute best verification score. The results are presented in Table 3-6.

BEST INDIVIDUAL OBJECTIVE FORECASTS

	JTWC	EXTRAP	ARAKAWA	700P	700PMOD	500P	RENARD	TYRACK
#TOP	76	49	66	11	29	15	14	34
CASES	282	279	265	235	134	227	224	256
RATE	.270	.176	.249	.043	.217	.066	.063	.133

TABLE 3-6

The JTWC forecast does not always produce the absolute best forecast but is more consistent. Cases where extrapolation or Arakawa produced a best forecast often involved a difference of only a few miles from the official forecast. Mean deviation from the JTWC forecast in these cases was

48 N.M. for extrapolation and 53 N.M. for Arakawa. This points out an area of potential improvement since 115 of 282 cases could have been improved by closer use of extrapolation or Arakawa objective techniques. Since all forecasts begin with extrapolation the remaining 167 forecasts must represent situations where extrapolation was correctly modified to produce a better official forecast. Further research aimed at developing procedural rules for limiting the deviation from Arakawa and extrapolation should improve some of the 18 cases in which the JTWC error was over 100 N.M. greater than extrapolation or Arakawa.

i. Tables 3-7 and 3-8 present stratified analyses of 1969 objective methods. Table 3-9 applies stratification by latitude to JTWC official forecasts. The 1969 sample is not large enough to guarantee representative figures in all stratifications but most results support previous observations. The following tentative conclusions based on stratification are offered:

(1) All computer methods except the 700 mb prog modified for 12 hour error performed best at higher latitudes with northeasterly moving storms. Arakawa did not work well at all for these storms. Extrapolation error was high due to acceleration. The 700P(MOD) provided a fair overall forecast for northeasterly moving storms.

(2) The most forecastable storms were those south of the ridge line. JTWC, Arakawa and extrapolation scored best on these. The 102 N.M. error for Arakawa on 77 westerly moving storms is very convincing.

(3) Stratification by wind extensity shows improved steering with increased intensity for all except the extrapolative techniques.

OBJECTIVE FORECAST STRATIFICATION
ERRORS BY DIRECTION OF MOVEMENT

	001-090°	091-259°	260-300°	301-360°
JTWC	152 (44)*	226 (15)	98 (74)	113 (77)
EXTRAP	179 (44)	246 (15)	110 (74)	130 (77)
ARAKAWA	231 (44)	218 (15)	102 (74)	121 (77)
700P	197 (44)	307 (15)	262 (74)	218 (77)
700P(MOD)	168 (30)	186 (10)	150 (39)	143 (45)
500P	205 (44)	457 (15)	290 (74)	258 (77)
RENARD	187 (44)	299 (15)	247 (74)	200 (77)
TYRACK	224 (44)	249 (15)	260 (72)	259 (77)

* Cases shown in parens

TABLE 3-7

OBJECTIVE FORECAST STRATIFICATION
ERRORS BY INTENSITY

MAX WINDS	<50 KT	≥50 KT	ALL WINDS
JTWC	132 (60)	121 (150)	124
EXTRAP	130 (60)	146 (150)	142
ARAKAWA	128 (60)	151 (150)	144
700P	286 (60)	215 (150)	235
700P(MOD)	186 (26)	146 (98)	154
500P	295 (60)	263 (150)	272
RENARD	277 (60)	198 (150)	221
TYRACK	282 (59)	239 (149)	251

* Cases shown in parens

TABLE 3-8

OFFICIAL JTWC FORECAST
STRATIFIED BY LATITUDE

	24 HR	48 HR	72 HR
SOUTH OF 20N	103 (132)	202 (63)	305 (16)
20N to 30N	117 (96)	240 (82)	346 (31)
SOUTH OF 30N	109 (228)	224 (145)	332 (47)
NORTH OF 30N	134 (20)	330 (21)	429 (10)
ALL CASES	111 (248)	237 (166)	349 (57)

* Cases shown in parens

TABLE 3-9

F. Confidence Forecasting.

1. BACKGROUND:

Forecaster confidence in his product is an often discussed parameter. If a forecaster were able to anticipate his good and bad forecasts, operational users would benefit from this information. In response to discussions of the 1969 Typhoon Conference an operational research project was designed to record and evaluate the accuracy of forecaster confidence at the time of forecast at JTWC.

2. PROGRAM SCOPE AND DESIGN:

The confidence forecast sample was 205 separate confidence forecasts from April through October of 1969. The sample included tropical storms as well as typhoons. The Director, Operations Officer or Typhoon Duty Officer completed a series of objective and subjective forecasts of confidence after each official warning but prior to the next aerial reconnaissance fix. The objective methods used were:

a. Area Climatology of Errors Based on Mean 1968 Experience: The assumption of this approach is that the difficulty of forecasting can be predicted from the location of the cyclone at the time of forecast.

b. Area Climatology by Category: This approach used the same data base as the first but makes only the category forecasts of average (110 N.M.) below average (70 N.M.) or above average (150 N.M.)

c. Mean Climatology: A representative mean climatology of 110 N.M. was applied to all forecasts.

d. Persistence: The 24 hour error determined at forecast time was forecasted to persist for the next 24 hours.

e. Subjective Forecast: Forecaster confidence in the subjective feeling a TDO has about his knowledge of where a cyclone is now, where it has been and where it is going. The following values were suggested from the 1968 season:

1st three warnings (no good 12 hour history)	150 N.M.
20 to 30 knot winds at forecast time	120 N.M.
Northeasterly movement	140 N.M.
Best confidence limit	40 N.M.
Worst confidence limit	200 N.M.

The original impetus for this study was the understandable desire to express statistically the increased confidence that was believed to accompany the reduction in forecasting error noted in the last few years thus enabling closer passage by mobile operating forces to tropical cyclones when forecaster confidence was better than average.

3. ANALYSIS:

a. General: Only the subjective method was significantly better than the other four methods tested. On the whole, forecasters' subjective estimates tended to be conservative, averaging 9 N.M. greater than observed mean error. Seventy-five percent (75%) of the confidence forecasts verified with errors no more than 20 N.M. greater than the forecast value. This figure compares with seventy-six point-five percent (76.5%) that would have verified under the same ground rules using a mean error value of 105 N.M. for all forecasts. The second method approximates the manner of applying confidence implied in current SEVENTH FLEET Operations Orders and presents a fair argument for retention of the present doctrine.

The relatively poor performance of the error forecasts by geographic area of origin is undoubtedly due in part to the limited sample size of the error climatology. Whenever 1968 error history was not available the mean value for 1968 was substituted. The relatively poor final performance of the area climatology, both mean values per 2 1/2 degree square and three category assignment, indicates negative correlation between forecast errors in the same geographic location from one year to the next. A tentative hypothesis for these data is that geographic errors are less significant than dynamic errors associated with storm intensity, speed of motion, direction of motion and its relation to large scale synoptic features of current weather charts. The expansion of error climatology based on geographic area would eventually produce a forecast showing some skill due to a concentration of storms with similar characteristics in the same area, but a more direct approach considering the dynamics of intensity or speed and direction of motion should be superior meteorologically.

The poorest of the objective methods is the persistance forecast. The results here indicate that large errors or small errors are unlikely to repeat themselves over a 48 hour period and also that forecasting of extreme values results in larger errors than forecasting mean values. We must conclude with some conviction that yesterdays performance is less indicative of todays confidence than is last years mean error value.

Even though the mean value of subjective forecaster confidence shows little skill over last years single mean value, the possibility of skill in one or more confidence categories is worth investigating.

b. Better Than Average Confidence (25 N.M. or less): Forecasts of good confidence are useful if (1) they can be reliably made and (2) they can result in a significant change in operational decisions. Relative to the first criterion, 12 of 49 confidence forecasts (24% of better than average confidence (85 N.M. or less) verified with greater than average error (135 N.M. or more.) From this we might describe a 76 percent confidence level that our forecast of "better than average" will verify as "average" or "better than average." Relative to the second criterion the best confidence used during the period was 50 N.M. The median error of the confidence forecast was 42 N.M. An operational decision at the 75 percent confidence level would **thus** involve the difference between a single mean error of 105 N.M. and the adjusted subjective forecast of 92 N.M. A maximum reduction of a "clearance criterion" for tropical storms of only 12 percent or 13 N.M. would result. Any of the 12 "bust" forecasts from the "better than average" forecast group might have encouraged a closer approach than would otherwise be considered prudent to the subsequent track of a typhoon if the confidence forecast were used in determining an evasion course. It is doubtful if the potentially small gain justifies the loss of confidence level.

c. Average Confidence (90 to 130 N.M.): One hundred five (105) of the two hundred five (205) forecasts in the sample were forecasted to be in the average range (90 to 130 N.M.) and only 21 of them (20%) verified with greater than average error. One would normally expect many more "bust" forecasts from the average confidence group than from the better than average group if predictable skill were involved.

d. Below Average Confidence (135 N.M. to 200 N.M.): Twenty-four (24) of fifty-one (51) below average confidence forecasts (47%) verified correctly in the above average error group suggesting considerable skill in the recognition of large error potential at the time of forecast. Even when circumstances of missing or questionable data create doubt in the forecasters mind and lead him to anticipate large potential errors, persistence works toward verifying a conservative extrapolation forecast. Verification of an expected large error with better than average accuracy is no indication of lack of forecaster skill. On the contrary it indicates that a difficult situation was recognized and correctly forecasted. The greater frequency of large errors in cases where they are expected would be valuable information to the Captain desiring to exercise all caution due an uncertain forecast of hazardous weather.

4. CONCLUSIONS:

a. Confidence as a forecast parameter is subject to the same range of inaccuracies experienced with other forecast parameters.

b. The best method of forecasting confidence found in the initial project was the subjective opinion of the forecaster.

c. The only occasion when a subjective confidence forecast showed significant skill was when large errors were anticipated.

G. Fujiwhara Effect - Case Studies.

1. INTRODUCTION:

There are many problems to be faced in tropical cyclone movement forecasting. One of these, which occurs only seldom but which is capable of injecting exceptionally high errors into movement forecasts, is the interaction of vortex centers with one another. This is often referred to as a demonstration of the Fujiwhara effect in honor of the first primary investigator of this phenomenon. This interaction or Fujiwhara effect is characterized by a cyclonic rotation of two vortex centers about some point located along a line connecting their two centers. This rotation is usually co-existant with a mutual attraction of the two vortex systems. The combined effects of rotation and attraction greatly affect forecast accuracy, since cyclone behavior deviates sharply from normal under these conditions.

Before forecast improvement can be achieved through practical application to compensate for the Fujiwhara effect, a better understanding of cyclone behavior under influence of binary interaction is necessary. To aid in this understanding, research was conducted on two cases of previous cyclone interaction. These cases were picked at random with the hope of obtaining cases representative of most occurrances.

Individual cyclone movement was investigated to see if it was feasible to combine cyclone rotation rates and some form of translation of a point common to both cyclones to obtain a reasonable estimate of actual individual cyclone speed of movement.

The first case investigated was that of Typhoons Kathy and Marie during the period 14/0000Z through 19/0000Z August 1964 (See Figure 3-7). The second case was that of Typhoons Marge and Nora during the period 24/1200Z through 28/1200Z August 1967 (See Figure 3-8).

The first case appeared to be a more classical example of binary cyclone interaction than the second case, but there was a definite interaction of the two cyclones in the second case also.

2. PROCEDURE:

The two cyclone tracks within each case were plotted on the same chart so that a visual representation of their relative interaction could be observed. Lines were drawn between each of the cyclone tracks connecting locations at corresponding times, so that angles of rotation could be determined. A midpoint between the cyclones along each connecting line was determined.

Though the use of the midpoint as the rotation pivot is a very simple method, it does not consider relative sizes of the interacting cyclones. Therefore a second set of rotation points was obtained to include a relative size factor. Many authors have theorized that rotation during binary cyclone interaction occurs about a point corresponding to the center of mass of the two interacting systems. Mass of any meteorological system is a very vague term and one which is hard to define. To incorporate this theory into an actual study, a previously suggested method using a maximum wind speed ratio was utilized using the following formula;

$$d_1=\frac{DV_2}{V_1}+ V_2 \qquad [1]$$

where

d_1 is the center of mass location from cyclone 1.

D is the total separation distance of the two cyclones.

V_2 is the maximum wind speed of cyclone 2.

V_1 is the maximum wind speed of cyclone 1.

By using these two points, the midpoint and the center of mass point, rates of rotation were determined. Afterward the translation speeds of these points of rotation were added with the rotation speed in hopes that a good approximation of actual cyclone speed could be determined. A twelve hour time period was used for all calculations. The following formulae were used:

$$S = S_r + S_t \qquad [2]$$

$$S_r = 1.4\text{X}10^{-3}\ \alpha\bar{r} \quad \text{(for 12 hour period)} \qquad [3]$$

$$S_t = D^*/12 \quad \text{(for 12 hour period)} \qquad [4]$$

where S: total speed of movement

S_r: speed of movement resulting from rotation.

S_t: speed of movement resulting from translation of the point of rotation.

α : angle of rotation over the 12 hour period.

$\bar{r}$: the average radius of rotation.

D^*: distance point of rotation moves in 12 hours.

NOTE: Direction of movement of the point of rotation relative to the direction of the cyclone rotation was not considered in calculated movement speeds.

3. DISCUSSION:

An analysis of the movement speed calculated by both the center of mass and the midpoint methods showed that in general the computed speed of movement was more accurate for the northernmost cyclone. The computed values for speed of movement for the southernmost cyclone were generally too high (See Figures 3-9 and 3-10).

One cyclone investigated, Typhoon Nora, fit these general observations but the calculated speeds were exceptionally unrealistic up to 27/0000Z. After that time calculated values compared favorably with the actual cyclone speed. At that time Nora became the northernmost cyclone of the pair and also began to show a slow intensification. This large error was probably caused by the fact that prior to 27/0000Z, Nora was just forming and moving very slowly. Her strength was only 20 knots or less during this period and she appeared to be no more than a weak, but well organized, tropical low.

Investigation of Case I (Typhoons Kathy and Marie) indicated that for Typhoon Kathy the center of mass point of rotation method gave exceptionally good results for the entire interaction period with an average error of only 1.5 knots. This was an average percentage of error of 27%. For Kathy the midpoint method gave good results also with an average error of 2.5 knots representing an average percentage of error of 36%.

For both methods, one time period was characterized by an unreasonable error. Estimated speeds for Kathy during the 12 hour period 17/1200Z to 18/0000Z were calculated as 7.5 knots and 7.1 knots for the center of mass method and the midpoint method respectively. During this time period Kathy was moving south, becoming the southernmost cyclone after previously being the northernmost cyclone. During this time the direction of rotation was perpendicular to the point of rotation movement therefore the rotation speed alone should have given the best estimation of the actual movement speed. The rotation speeds for the center of mass method and the midpoint method were 5.6 knots and 6.8 knots, respectively. These compared more favorably to the actual movement speed of 4 knots.

The average results for Typhoon Marie were comparable to the results obtained for Kathy with an average error of 2.7 knots when the midpoint method was used. This corresponded to an average percent of error of 32.9%. When the center of mass method was used a much greater average error of 5.9 knots and an average percent of error of 60.6% was obtained. A look at Figure 3-9 shows that after 17/0000Z the errors for the midpoint method decreased and remained fairly accurate. At that same time the center of mass method increased in accuracy but after 18/0000Z the accuracy decreased significantly. It was found that for every time there were poor comparisons the cyclone was either moving at large angles to or in the opposite direction to the movement of the rotation point. This indicates that a component of the point of rotation movement speed relative to the direction of movement of the cyclone should be considered in order to achieve the best results.

It was also observed that the original northernmost cyclone actually slowed to a minimum movement speed about 6 to 12 hours after the calculated speeds of both the midpoint and the center of mass methods indicated a minimum in speed. At the time the two interacting cyclones became east and west of each other the cyclone moving south tended to slow sharply in movement while the cyclone moving north began to accelerate. Shortly before this the point of rotation either slowed in movement speed or became erratic in movement.

Investigation of Case II (Typhoons Marge and Nora) indicated that the midpoint method gave slightly better results for both cyclones considered together, but neither method gave good results for Nora until 27/0000Z. As mentioned earlier, before this time Nora was only a weak developing tropical low and as such her movement is considered unrepresentative of normal cyclone movement under Fujiwhara effects.

Excluding the results for Typhoon Nora, the comparison of actual versus computed speeds of movement for this case compared favorably with those of Case I. The speeds of movement calculated for Typhoon Marge indicated that the center of mass method gave slightly better results for the overall investigated time interval. The center of mass method gave an average error of 2.3 knots as compared to 2.5 knots for the midpoint method. The corresponding average percents of error were 31.2% and 38.7%, respectively (See Table 3-10). The midpoint method gave exceptionally good results during the first part of the investigation period up to 27/1200Z with an average error of 1.0 knots and an average percent of error of 8.4%. Both methods were very good until 27/0000Z.

After 27/0000Z, Marge became the southernmost cyclone as the two cyclones slowly rotated. After that time the cyclone's movement was perpendicular to or in the opposite direction of the rotation point movement. This case, therefore, also indicates that more accurate results could be obtained by using the component part of the rotation point movement corresponding to the cyclone movement.

Although Nora was very weak during the initial time period of this case study, she evidently had some definite influence on the movement of Typhoon Marge. Nora was too weak in comparison to Marge to ever cause a full rotation but she was able to alter the track and speed of Marge (See Figure 3-8). At the time when Nora moved north of Marge's 090° bearing, attraction of the two cyclones seemed to cause a rapid deceleration of Marge and shortly thereafter Marge experienced a change in direction to a north of west course.

As noticed in Case I, the points of rotation for Case II slowed in movement or changed direction abruptly approximately 6 to 12 hours preceding a decrease in the speed of movement of the cyclone moving toward the south. (See Figure 3-10.)

The angle of rotation (α) is one of the major variables contributing to the estimation of a cyclone speed of movement while experiencing Fujiwhara effect. Since little is known about what elements cause significant changes in values of α, a short investigation of its characteristics evident in these two case studies was conducted. It appears that there is some influence on α caused by changes in intensity differences of the two interacting cyclones and changes in the average distance of separation. An investigation of this variance of α in relation to values of intensity differences compared with cyclone separation indicated that an increase in α occurs with a decrease in separation distance and an increase in the intensity difference of the two cyclones. It also appears that very little rotation occurs at separation distances greater than 600 or 700 N.M. no matter what the intensity difference is. See Figure 3-11.

4. CONCLUSION:

The results of this research indicate that cyclone speed of movement during interaction can be closely approximated by theoretical calculations which combine the rotational effect of the cyclones and the translation of the point of rotation.

Results were exceptionally good when the cyclone was moving in the same direction as the point of rotation. It was also noticed that when a cyclone was moving in an opposite direction to that of the rotation point better results were achieved by subtracting the translation speed of the rotation point. For inbetween cases, such as when the cyclone was moving at angles to the direction of movement of the rotation point, calculated speeds would be improved by adding or subtracting only that component of movement speed of the rotation point that corresponded to the direction of movement of the cyclone.

Consideration of cyclone intensity by using the center of mass method was necessary only for cases of excessive difference in the intensity of two cyclones. Even for excessive intensity differences the midpoint method will generally give satisfactory results.

By using the translation of the point of rotation as a contributor to the cyclone speed of movement, we are assuming that the speed of movement of the rotation point is in direct proportion to the steering flow. We are also assuming that the steering flow is homogeneous for the entire rotating system, which requires the horizontal shear to be zero. This is a tenuous assumption since horizontal shears are seldom zero over an area as large as that representing these rotating systems. Therefore it must be concluded that the presence of excessive or large horizontal shears can definitely inject significant errors into speed calculations.

It was noticed during analysis of computed cyclone movement speeds and the corresponding actual cyclone movement speeds that at the time the points of rotation began to slow in translation speed or became erratic in movement, the cyclone pairs reacted much in the same manner for both cases. At the time the point of rotation began to slow or became erratic, the cyclone moving toward the south slowed in movement within the following 6 to 12 hour period while the cyclone moving north began to increase in speed of movement within the next 6 to 12 hours. After firm substantiation by investigation of several more cases, this observed reaction could prove beneficial in the short range forecasting of changes in cyclone speed of movement of two interacting cyclones.

There are definite possibilities for future use of binary cyclone interaction theories for assisting in forecasting movements of interacting cyclones but considerably more research is needed before a reliable forecast tool evolves. From equations [2], [3], and [4], we can see that if S_r and S_t can be predicted with reasonable accuracy for a period of time, say 12 hours, then an average speed of movement of the cyclone can be obtained for that 12 hour period. Keep in mind that a component of S_t would have to be added or subtracted from S_r, depending upon an estimated direction of movement for the cyclone in question. It appears that a reasonable answer could be reached simply by adding S_t to S_r for a westward moving cyclone and subtracting S_t from S_r for an eastward moving cyclone.

Now that the use of the predicted S_r and S_t is necessary, we come to the perplexing problem of how a prediction of S_r and S_t can be reached. Although not researched in this study, it appears that a reasonable value for S_t could be reached by steering the rotation point with the integrated steering flow much as would be done for forecasting the movement of a single cyclone. (The possible errors in using this method were suggested earlier when discussing the assumption of a horizontally homogeneous atmosphere over the interacting system). Prediction of S_t is difficult enough but the prediction of S_r at this state of the art is even more difficult. From equation [3] it is noticed that a value for S_r is dependent upon the angle of rotation for a predetermined time period (α) and upon the average radius of rotation ($\bar{r}$). A reasonable value for $\bar{r}$ can be reached by forecasting the expected distance separating the two cyclones, considering mutual attraction, and if desired, by also using an estimated intensity of each cyclone. A prediction method for α is the major "weak link" in the chain. Present knowledge of the mechanisms causing significant changes in the rotation rates remains at a rather primitive level.

It may be possible in the future to obtain a reasonable approximation for the angle of rotation from a graph similar to that in Figure 3-11. For this to be feasible, investigation of many more case studies will be required to increase the density of data points to obtain consistently reliable estimates of the angle of rotation.

As a result of this investigation, it is definitely indicated that cyclone movement during interaction can not be fully explained or forecasted by the use of simple techniques, but continued research in this area has good potential for assisting in lowering errors in the forecasting of tropical cyclone movement.

MOVEMENT ERROR (CALCULATED VS. ACTUAL)

		MIDPOINT		CENTER OF MASS	
		Average Error	Average % Error	Average Error	Average % Error
CASE I	Kathy	2.5 kts	36.0%	1.5 kts	26.5%
	Marie	2.7 kts	32.9%	5.9 kts	60.6%
CASE II	Marge	2.5 kts	38.7%	2.3 kts	31.2%
	Nora	7.7 kts	223.5%	11.4 kts	361.5%

TABLE 3-10

REFERENCES:

1. Annual Typhoon Report, U. S. Fleet Weather Central/Joint Typhoon Warning Center, Guam, 1964 and 1967.

2. Brand, Samson, Interaction of Binary Tropical Cyclones of the Western North Pacific Ocean, NAVWEARSCHFAC Technical Paper No. 26-68, Norfolk, Va., 1968.

3. Riehl, H., Tropical Meteorology, McGraw-Hill Book Company, Inc., New York, 1954, Pg. 345-347.

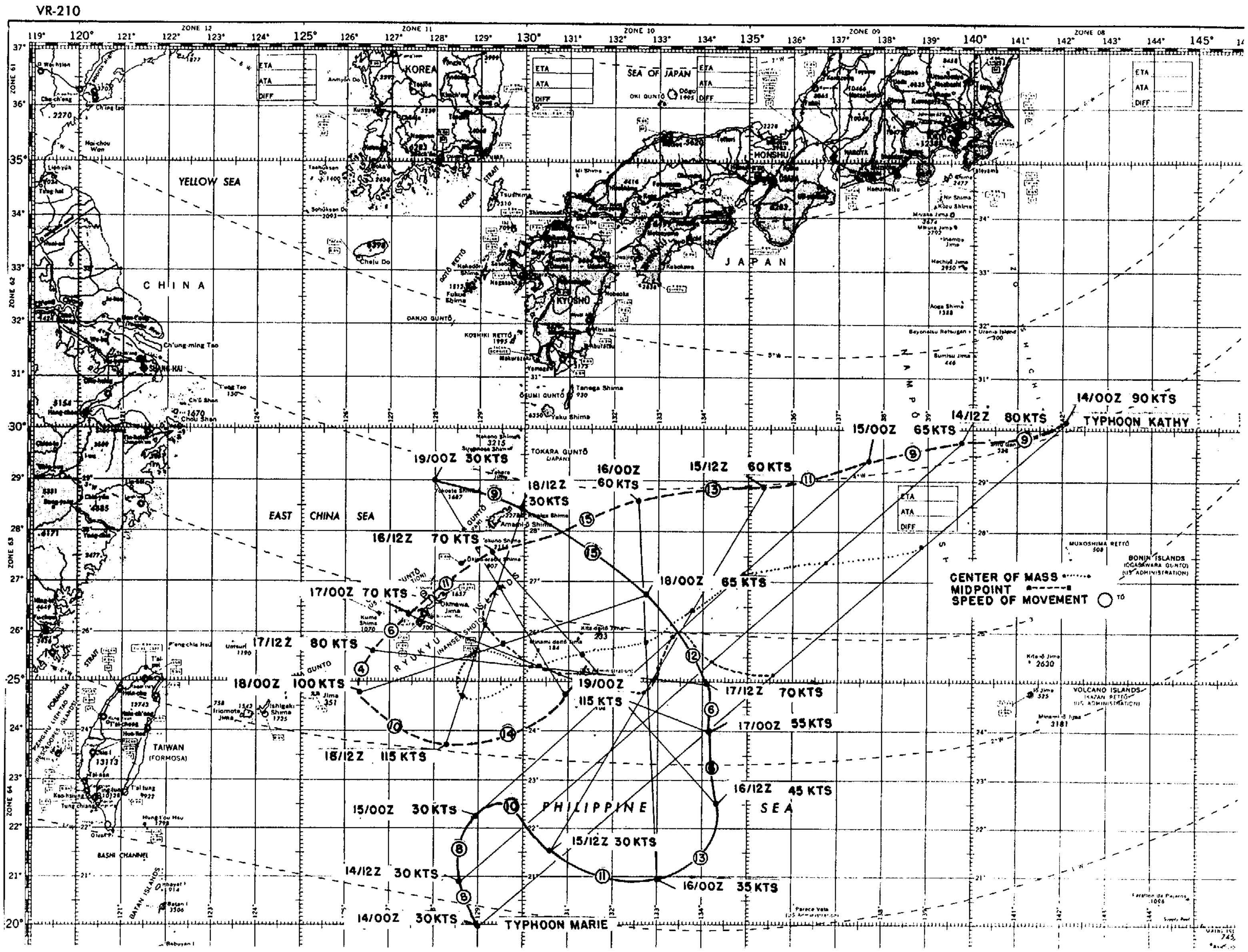

VR-210
YELLOW SEA
CHINA
KOREA
SEA OF JAPAN
JAPAN
HONSHU
KYUSHU
EAST CHINA SEA
TAIWAN (FORMOSA)
PHILIPPINE SEA
BONIN ISLANDS
VOLCANO ISLANDS
ETA
ATA
DIFF
TYPHOON KATHY
14/00Z 90 KTS
14/12Z 80 KTS
15/00Z 65 KTS
15/12Z 60 KTS
16/00Z 60 KTS
16/12Z 70 KTS
17/00Z 70 KTS
17/12Z 80 KTS
18/00Z 100 KTS
18/12Z 30 KTS
19/00Z 30 KTS
TYPHOON MARIE
14/00Z 30 KTS
14/12Z 30 KTS
15/00Z 30 KTS
15/12Z 30 KTS
16/00Z 35 KTS
16/12Z 45 KTS
17/00Z 55 KTS
17/12Z 70 KTS
18/00Z 65 KTS
19/00Z 115 KTS
16/12Z 115 KTS
CENTER OF MASS
MIDPOINT
SPEED OF MOVEMENT

FIGURE 3-7

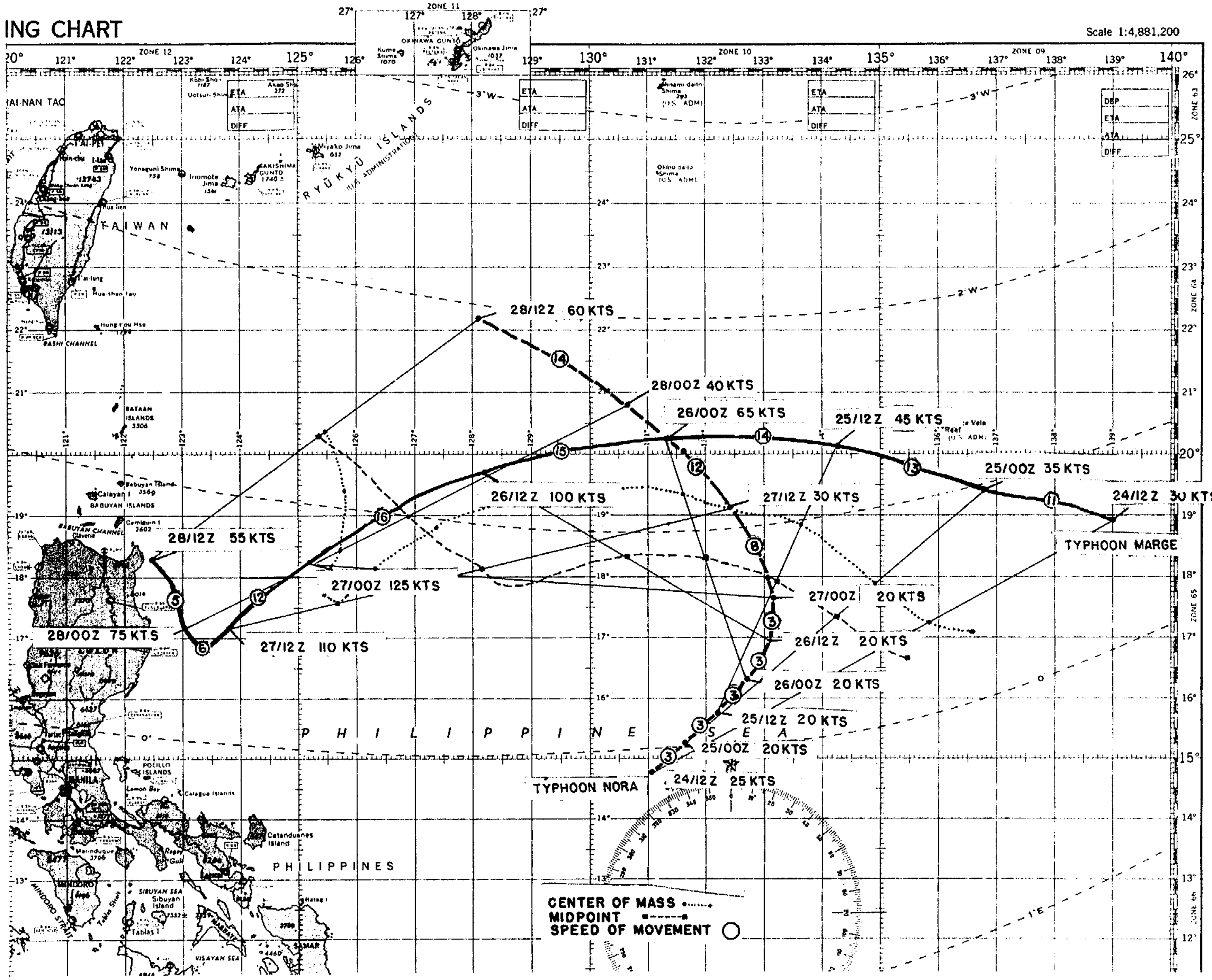
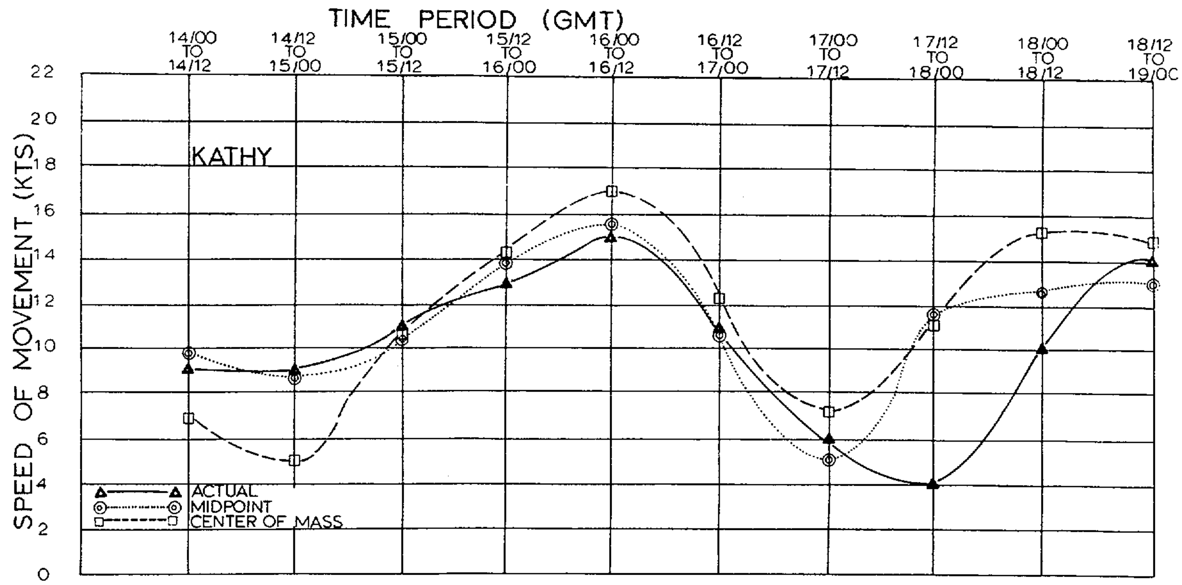

ING CHART
Scale 1:4,881,200
VR-208
TAIWAN
PHILIPPINE SEA
PHILIPPINES
RYUKYU ISLANDS
28/12Z 60 KTS
28/00Z 40 KTS
26/00Z 65 KTS
25/12Z 45 KTS
25/00Z 35 KTS
24/12Z 30 KTS
TYPHOON MARGE
26/12Z 100 KTS
27/12Z 30 KTS
28/12Z 55 KTS
27/00Z 125 KTS
27/00Z 20 KTS
28/00Z 75 KTS
27/12Z 110 KTS
26/12Z 20 KTS
26/00Z 20 KTS
25/12Z 20 KTS
25/00Z 20 KTS
24/12Z 25 KTS
TYPHOON NORA
CENTER OF MASS
MIDPOINT
SPEED OF MOVEMENT

FIGURE 3-8


TIME PERIOD (GMT)
14/00 TO 14/12
14/12 TO 15/00
15/00 TO 15/12
15/12 TO 16/00
16/00 TO 16/12
16/12 TO 17/00
17/00 TO 17/12
17/12 TO 18/00
18/00 TO 18/12
18/12 TO 19/00
SPEED OF MOVEMENT (KTS)
KATHY
ACTUAL
MIDPOINT
CENTER OF MASS

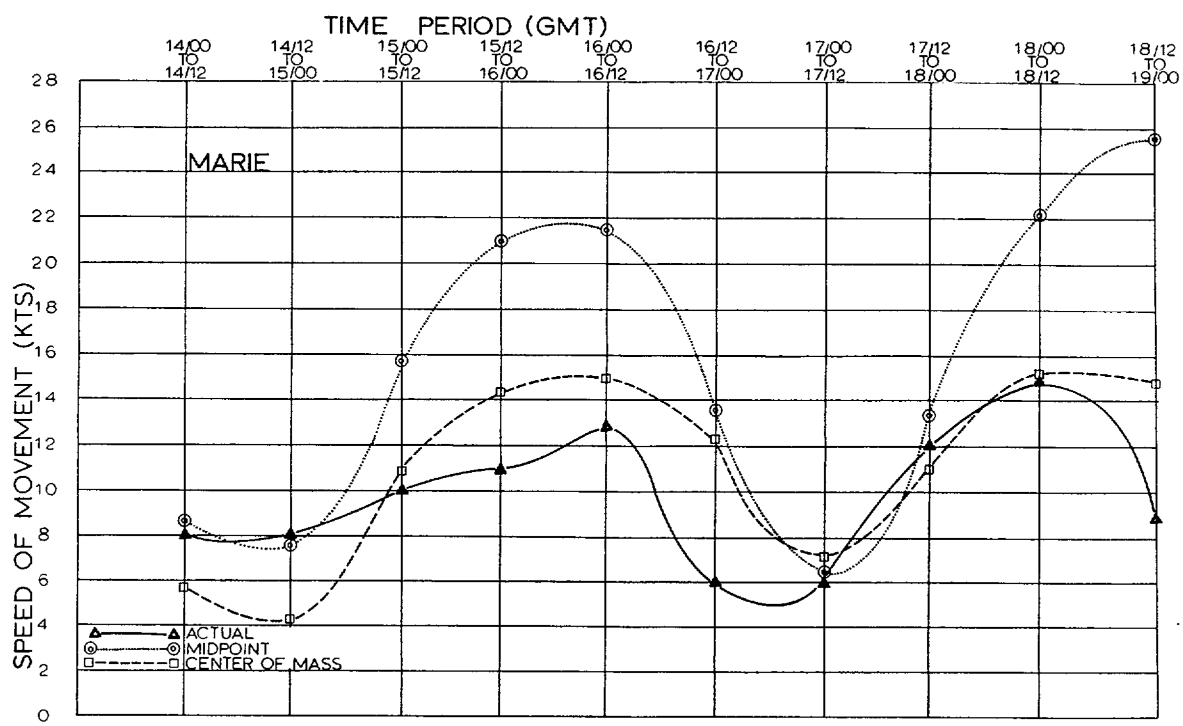
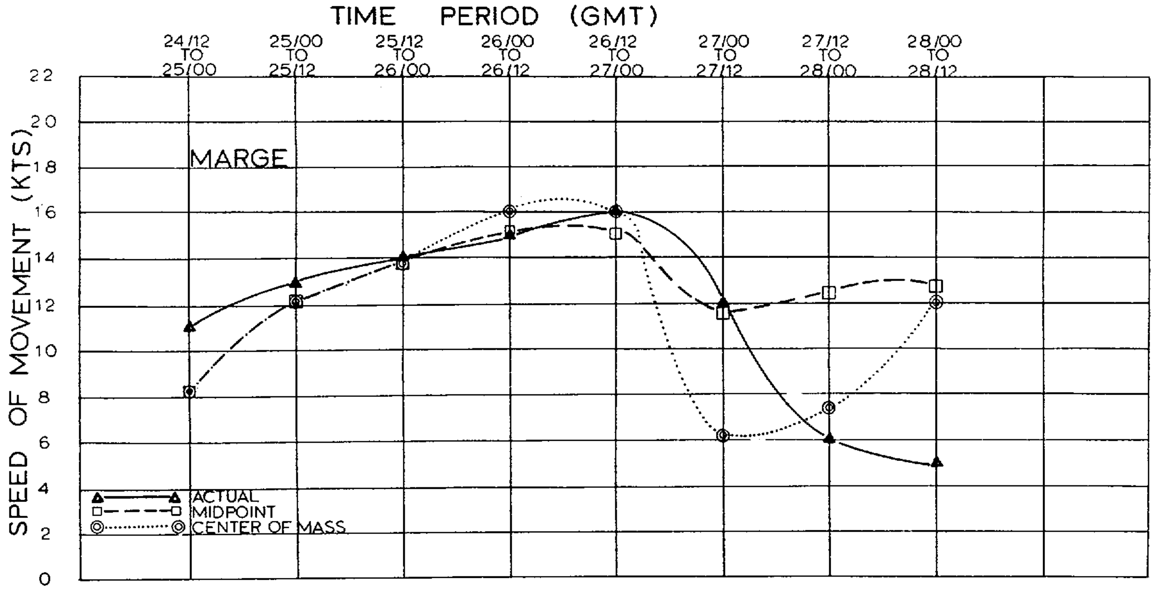

TIME PERIOD (GMT)
14/00 TO 14/12
14/12 TO 15/00
15/00 TO 15/12
15/12 TO 16/00
16/00 TO 16/12
16/12 TO 17/00
17/00 TO 17/12
17/12 TO 18/00
18/00 TO 18/12
18/12 TO 19/00
SPEED OF MOVEMENT (KTS)
MARIE
ACTUAL
MIDPOINT
CENTER OF MASS

FIGURE 3-9


TIME PERIOD (GMT)
24/12 TO 25/00
25/00 TO 25/12
25/12 TO 26/00
26/00 TO 26/12
26/12 TO 27/00
27/00 TO 27/12
27/12 TO 28/00
28/00 TO 28/12
SPEED OF MOVEMENT (KTS)
0
2
4
6
8
10
12
14
16
18
20
22
MARGE
ACTUAL
MIDPOINT
CENTER OF MASS

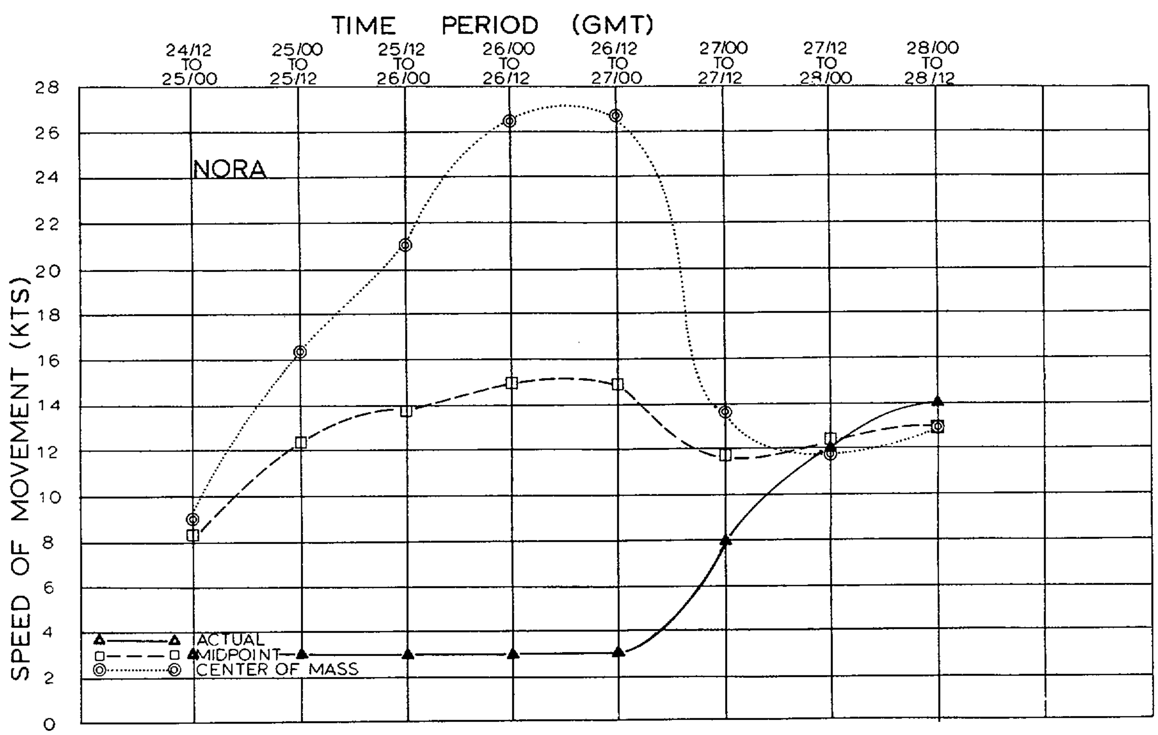

TIME PERIOD (GMT)
24/12 TO 25/00
25/00 TO 25/12
25/12 TO 26/00
26/00 TO 26/12
26/12 TO 27/00
27/00 TO 27/12
27/12 TO 28/00
28/00 TO 28/12
SPEED OF MOVEMENT (KTS)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
NORA
ACTUAL
MIDPOINT
CENTER OF MASS

FIGURE 3-10

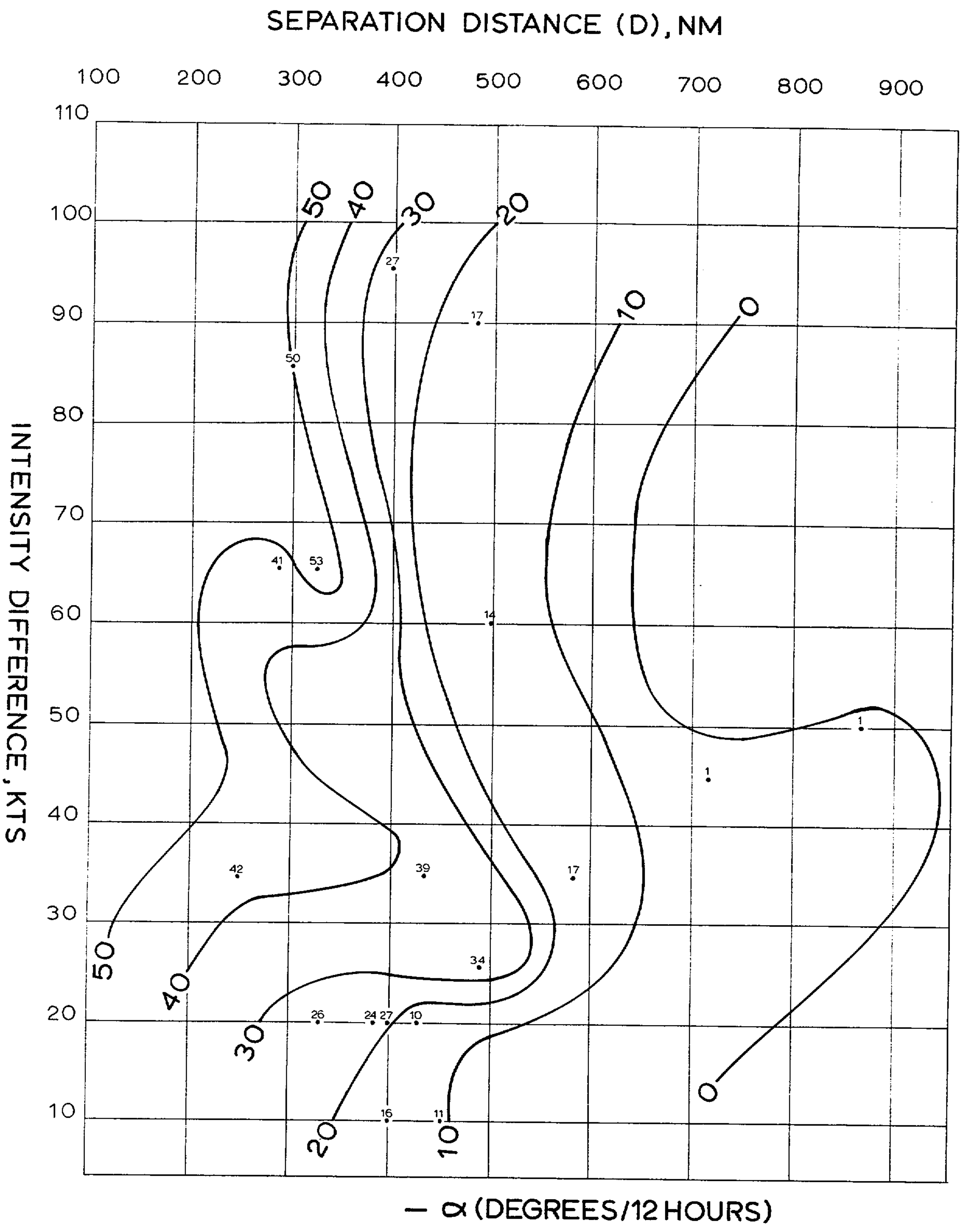

SEPARATION DISTANCE (D), NM
100
200
300
400
500
600
700
800
900
INTENSITY DIFFERENCE, KTS
110
100
90
80
70
60
50
40
30
20
10
50
40
30
20
10
0
— α (DEGREES/12 HOURS)

FIGURE 3-11

H. Climatology

1. TYPHOON FREQUENCY:

Typhoon frequency climatology was slightly decreased by the small number of occurrances experienced this season. The average annual typhoon frequency decreased from 20.6 at the end of the 1968 season to 19.9 at the end of this season (See Table 3-11).

2. TYPHOON DISTRIBUTION:

Figure 3-12 depicts the typhoon distribution of 347 typhoons which have been detected over the past 18 year interval. Notice that the months of high formation probability remain the months of July through November after the inclusion of 1969 typhoon data.

TYPHOON FREQUENCY
11 YEAR PERIOD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL TOTAL
1959	0	0	0	1	0	0	1	5	3	3	2	2	17
1960	0	0	0	1	0	2	2	8	0	4	1	1	19
1961	0	0	1	0	2	1	3	3	5	3	1	1	20
1962	0	0	0	1	2	0	5	7	2	4	3	0	24
1963	0	0	0	1	1	2	3	3	3	4	0	2	19
1964	0	0	0	0	2	2	6	3	5	3	4	1	26
1965	1	0	0	1	2	2	4	3	5	2	1	0	21
1966	0	0	0	1	2	1	3	6	4	2	0	1	20
1967	0	0	1	1	0	1	3	4	4	3	3	0	20
1968	0	0	0	1	1	1	1	4	3	5	4	0	20
1969	1	0	0	1	0	0	2	3	2	3	1	0	13
AVG	.2	0	.2	.8	1.1	1.1	3.0	4.5	3.3	3.3	1.8	.7	19.9

TABLE 3-11

18 YEAR MONTHLY DISTRIBUTION OF 347 WESTERN PACIFIC TYPHOONS 1952 — 1969

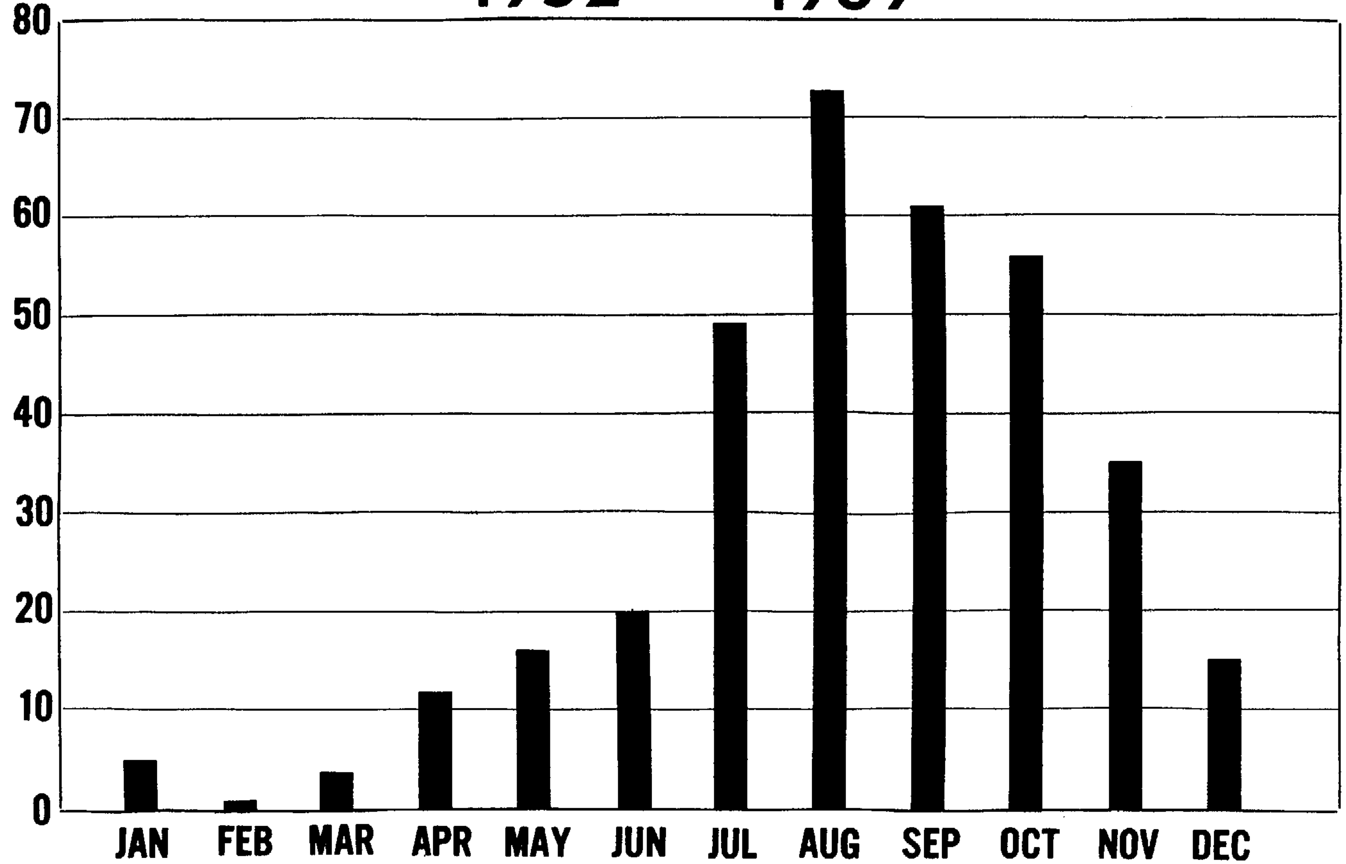


FIGURE 3-12

I. Satellite Data Fix Accuracy.

1. BACKGROUND:

A study of satellite fix accuracy was presented in the 1966 Annual Typhoon Report. Since that time a new generation of space hardware and improved technology have been developed. This study was made to reflect any improvements in terms of fix data reliability.

2. METHOD:

Satellite bulletin fix positions were compared to the JTWC best track positions for the time of the satellite fixes. Results are reported in Table 3-12.

SATELLITE POSITION ERROR (N.M.)

	1965	1966	1969
NUMBER OF CASES	75	71	75
AVERAGE ERROR	81	49	39
MEDIAN ERROR	55	39	34
RANGE OF ERROR	0-425	5-219	5-105

TABLE 3-12

3. CONCLUSIONS:

Slight improvement since 1966 is indicated, however, 1969 figures were limited to storms whose best track wind velocities were 35 knots or greater. This eliminates the main source of disproportionately high errors during the formative stages and may account for some apparent gain in accuracy. The 1969 mean and median position errors represent the practical total resolution presently available from satellite systems relative to location of tropical cyclones.